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ORIGINAL ARTICLE

Prediction of compaction caused by the transit in sugarcane harvesting

Predicción de la compactación provocada por el tránsito en la cosecha de caña de azúcar

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ABSTRACT: Soil compaction due to agricultural machinery traffic is a threat to soil productivity and soil ecological functions. The prediction of soil stresses and compaction that soil bear during the harvest and transport are fundamental indications in the prevention strategies and remediation of the soil compaction. The objective of this research was to predict soil compaction caused by harvesters and transport equipment during sugarcane harvest on soft soil. Machinery traffic was simulated using the TASC V3.0 model, Module 1 "Stress Propagation and Soil Damage" was used. The machine system used for harvest sugarcane were formed by harvesters CASE IH 8800, and tipping tows 7CX (SC)-10 pulling by tractors YTO 1608 or XTZ 150K-09. Parameters from machinery and soil are introducing as data. The use of modelling TASC V3.0 permitted to predict soil compaction caused by harvesters and transport equipment during sugarcane harvest on soft soil. More severe soil compaction was obtained during use of tipping tow 7CX (SC)-10 due to high mean contact pressure and high tire load, which caused severe soil compaction until a depth of 0.37 m. Rear tire of tractor YTO 1604 caused severe soil compaction too reaching 0.31 m of depth. In general sense all equipment caused severe soil compaction in tillage layer, therefore must be make decompactions works with the objective to loose soil in depth for a good developed of sugarcane ratoons.

***Keywords*: Mean Contact Pressure, Soft Clay Soil, TASC V3.0.**

RESUMEN: La compactación del suelo debido al tráfico de maquinaria agrícola es una amenaza para la productividad y las funciones ecológicas del suelo. La predicción de los esfuerzos del suelo y la compactación que soporta el suelo durante la cosecha y el transporte son indicaciones fundamentales en las estrategias de prevención y remediación de la compactación del suelo. El objetivo de esta investigación fue predecir la compactación del suelo causada por cosechadoras y equipos de transporte durante la cosecha de caña de azúcar en suelos blandos. El tráfico de maquinaria se simuló utilizando el modelo TASC V3.0, se utilizó el Módulo 1 "Propagación de Esfuerzos y Daño al Suelo". El sistema de máquinas utilizado para la cosecha de caña de azúcar estuvo formado por cosechadoras CASE IH 8800, y remolques basculantes 7CX (SC)-10 tirados por tractores YTO 1608 o XTZ 150K-09. Se introducen como datos parámetros de maquinaria y suelo. El uso del modelado TASC V3.0 permitió predecir la compactación del suelo causada por cosechadoras y equipos de transporte durante la cosecha de caña de azúcar en suelos blandos. Se obtuvo una compactación del suelo más severa durante el uso del remolque basculante 7CX (SC)-10 debido a la alta presión media de contacto y la alta carga de los neumáticos, lo que provocó una compactación severa del suelo hasta una profundidad de 0,37 m. El neumático trasero del tractor YTO 1604 provocó una fuerte compactación del suelo alcanzando 0,31 m de profundidad. En sentido general todos los equipos ocasionaron una severa compactación del suelo en la capa de labranza, por lo que se deben realizar trabajos de descompactación con el objetivo de aflojar el suelo en profundidad hasta 0.37 m para un buen desarrollo de los retoños de caña de azúcar.

***Palabras clave*: Presión media en el contacto, suelo arcilloso blando, TASC V3.0.**

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INTRODUCTION

Soil compaction due to agricultural traffic machinery is a threat to soil productivity and soil ecological functions (Guimarães *et al*., 2017). Compaction affects the environmental sustainability of soil, and cause soil degradation. Land degradation is a deterioration of long-term in ecosystem function and productivity caused by alterations starting from which soil cannot recover without help, this is a cumulative global issue, growing from 15 per cent of the total land surface in 1991 to 24% in 2008 (Bai *et al*., 2008).

If the pressure exerted on the soil by traffic of agricultural equipment is smaller than the soil strength, no permanent deformation will occur and hence soil damage is not to be expected. If this is not the case, then soil compaction is unavoidable (Schjønning *et al.*, 2015, Stettler *et al*., 2014). ASAE/ASABE S526.4(R2019) (2015) defined soil compaction as the reduction in porosity, and collapse of the structure of soil when subjected to surface loads. It damages the physical basis of soil fertility, it increases the mechanical resistance for root growth and modifies the soil pore size distribution and connectivity. It decreases infiltration and groundwater recharge, as well as increasing water runoff, soil erosion, and flooding (Berli *et al*., 2015, Keller *et al*., 2015, Kuhwald *et al*., 2018).

Soil compaction in cultivated lands affects mostly the upper layer of soil (Nawaz *et al*., 2013). Topsoil compaction takes place in the soil tillage layer and subsoil compaction takes place to depth under soil tillage layer (Alakukku et al., 2003). Primary tillage may reverse topsoil compaction, but subsoil compaction persists in the long term (Kuhwald *et al*., 2018). Researches of long-term found that subsoil compaction is not alleviated by natural processes and that nutrient leaching and greenhouse gas emissions may be intensified (Stettler *et al*., 2014).

At the present days heavy tractors are increasingly used in intensive farming because it offers the possibility of working with a minimum number of passes on agricultural soil (Biris *et al*., 2019). These tractors have driving systems on tracks or high flotation tires, this way no high pressures on soil surface are achieved. However, subsoil compaction due to tractor traffic is directly related to axle load (Botta *et al*., 2002, Botta *et al*., 2009, González *et al*., 2016). Soil stress is always a function of the stress at the tire-soil interface, which is a function of both tire inflation pressure and wheel load, as well as tire properties and soil conditions (Arvidsson and Keller, 2007).

The main factors that cause soil compaction are related with machinery traffic and soil properties. Axle load, ground pressure, tire inflation pressure, stresses distribution on soil surface, traffic intensity, speed forward, and travel reduction are machinery features related to soil compaction (Biris *et al*., 2009, González *et al*., 2009, González *et al*., 2013, Kuhwald *et al*., 2018, Nawaz *et al*., 2013). The soil texture, soil grain size, or soil type (Biris *et al*., 2019, González *et al*., 2013, Nawaz *et al*., 2013, Silva *et al*., 2018), structure, organic matter content, bulk density, soil moisture content (de Lima *et al*., 2018, González *et al*., 2013, Silva *et al*., 2018) and soil stress history they are associated to soil strength and consequently to soil compaction (Berli et al., 2015, Guimarães Júnnyor et al., 2019). But it is heavily dependent of wet soil (Botta *et al*., 2016, Chamen *et al*., 2015, Guimarães Júnnyor *et al.*, 2019, Kuhwald *et al*., 2018, Stoessel *et al*., 2018).

Among factors influencing soil compaction the soil moisture content is the most important factor (Hamza and Anderson, 2005). González *et al*. (2008) on laboratory conditions evaluated the effect of soil moisture content and the ground pressure in soil porosity. They found that a ground pressure of 400 kPa, on a Rhodic Ferralsol soil with 25% of moisture content, causes a smaller change in the porosity that a ground pressure of 200 kPa in a soil with 35% of moisture content. The soil moisture content has a bigger influence in the porosity decrease that ground pressure. What means, that increasing soil moisture content causes a reduction of soil strength (Hamza and Anderson, 2005).

The prediction of soil stresses and compaction have been modelling by mean of numerical and semi-analytical methods (Défosssez and Richard, 2002). The numerical method more used have been finite element method (González *et al*., 2013, Nawaz *et al*., 2013, Silva *et al*., 2018, Biris *et al*., 2019) . Analytical or semi-analytical soil compaction models have the advantage that they are usually simple to use, and require few input parameters. These methods have been widely used in modeling of soil compaction achieving satisfactory predictions of stress transmission and change of bulk density (Keller and Lamandé, 2010). Among these models it is found SOCOMO developed to calculate soil stresses under wheel loads (Van den Akker, 2004), SoilFlex, a model for prediction of soil stresses and soil compaction due to agricultural traffic. This model allows predictions of the contact area and the stresses distribution in the contact area from readily available tire parameters, it is possible to simulate the passage of several machines, including e.g. tractors with dual wheels and trailers with tandem wheels (Keller *et al*., 2007). Schjønning *et al*. (2008) proposed the model FRIDA that describes the tire footprint by a super ellipse and the stress distribution by a combined exponential (perpendicular to the driving direction) and power-law (along the driving direction) function. The model seems suited for describing stress distributions at the soil-tyre interface.

Battiato and Diserens (2017) developed a model to predict subsoil compaction TASC (TYRES/TRACKS AND SOIL COMPACTION) as an Excel application consisting of five modules. The first module permits rapid evaluation of the risks of severe soil-compaction damage in the subsoil by taking into account both soil characteristics and machine load and the second module simulates the traction force - slip curve providing also the limit beyond which top soil failure occurs. The others modules calculates the share of trafficked areas, provides access to the technical data for more than 1,270 agricultural and forestry tires and final module related to road safety provides information (Diserens *et al.*, 2014). This model have been applied by Guimarães Júnnyor et al. (2019) to prediction of soil stresses and compaction due to agricultural machines in sugarcane cultivation systems. The results indicated strategies to avoid soil compaction by machines, including adjustments on machine loads and changes in tillage and management design.

In Cuba, the sugarcane has always taken an outstanding place as for the quantity of area dedicated to its cultivation, reaching in the season 2020-2021 the 300 000 ha harvested (ONEI, 2023). The use of heavy harvesters and transport equipment has been identified as one of the main causes of soil compaction in sugarcane crop in Cuba (López-Bravo *et al.*, 2022). Some areas planted with sugarcane, in heavy clay plastics soils during intense rains they cannot be harvested by several weeks and until months due to the high water content that soil store, causing considerable economic losses (Martínez-Ramírez *et al.*, 2017).

The mill José Maria Pérez, in Camajuaní, province of Villa Clara, in the central region of Cuba, it has areas with Vertisol soils (Hernández *et al.*, 2015). In the farm Chiqui Gómez Lubian, belonging to this mill, the harvest of sugarcane is made with CASE IH 8800, tipping tows 7CX (SC)-10 pulling by tractors YTO 1608 or XTZ 150K-09. These soils remain wet during several days or weeks after intense rains and in many cases the harvest is carried out in soft soil conditions, which favors the soil compaction.

After harvester the agricultural operations to reestablish the initial state of the soil in the plantation, are one of the main tasks in search of achieving a good yield of the ratoons. The prediction of soil stresses and compaction that soil bear during the harvest and transport are fundamental indications in the prevention strategies and remediation of the soil compaction. The objective of this research was to predict soil compaction caused by harvesters and transport equipment during sugarcane harvest on soft soil.

MATERIAL AND METHODS

Machinery traffic was simulated using the TASC V3.0 model (Battiato and Diserens, 2017). Module 1 "Stress Propagation and Soil Damage" was used. The procedures used to calculate the soil stresses in depth, the determination of the depth at which severe compaction occurs, as well as tire/track soil contact area and the mean contact pressure can be reviewed in Diserens (2009), Diserens *et al.* (2010), Diserens *et al.* (2011) and Diserens et al. (2014).

2.1. Soil Simulation

Several are the input data necessary for soil simulation. a) Soil moisture. The model includes two characteristic soils such as forestry and farming soils. Two options of soil moisture must be selected: farming humid soil at 1.8 pF or farming dry soil at 2.5 pF. The farming humid soil was selected. b) Soil texture at the maximum tillage depth. The model shows five soil textures for select one and one user defined. From clay soil to loam, silty or sandy soil. If the clay and silt soil content is available, the user defined box is used and both contents are entered into the software. Clay soil was selected. c) Maximum tillage depth. Maximum depth at which tillage work is carried out and the soil is loosened.

The tillage depth generally used in the investigated area is 0.20 m. d) Hardness topsoil. The model calculates the stress distribution for three hardness topsoil firm, semi-firm and soft) or user defined. Soft soil was selected.

2.2. Machinery Simulation

The machine system used for harvest sugarcane were formed by harvesters CASE IH 8800, and tipping tows 7CX (SC)-10 pulling by tractors YTO 1608 or XTZ 150K-09. Parameters from machinery are introducing as data. Technical data for more than 1270 agricultural and forestry tires are available in TASC for input data. Tire/track type is the relationship tire height and tire width or track; Tire structure is a selection between bias or radial tire ply; Tire track width is tire width or track width; Tire diameter/track length. These parameters are introduced automatically if the tires were selected from data tables. Tire/track load is the maximum tire/track load in kg. Tire inflation pressure is internal tire pressure in bar. The tires load was determined weighing the axle load and later divided by two. Tire inflation pressure was determined with a manometer. Table 1 shows data of the machinery and the tire/track used as input in TASC.

RESULTS AND DISCUSSION

The results of the simulation as mean contact pressure, severe soil compaction risk up to depth and maximum vertical stresses propagated to soil are

TABLE 1. Dataset Input of Machinery Evaluated

Machinery	Axle	Tire Size	Data entered into TASC V3.0					
			Tire/ Track Type	Tire Structure	Tire/Track Width (m)	Tire Diameter/ Track length (m)	Tire/Track Load (Mg)	Tire Inflation Pressure (kPa)
Tractor XTZ 150K-09	Front	21.3-24	d	ni	0.52	1.31	2.34	170
Tractor XTZ 150K-09	Rear	21.3-24	d	ni	0.52	1.31	2.12	170
YTO 1604	Front	460/85R34	r	no	0.48	1.66	1.97	130
YTO 1604	Rear	18.4-38	d	no	0.47	1.77	2.85	280
Tipping Tow 7CX (SC)-10	Front	600/50-22.5	d	tr	0.60	1.17	4.04	290
Tipping Tow 7CX (SC)-10	Rear	600/50-22.5	d	tr	0.60	1.17	3.19	290
CASE IH 8800		Track	ra		0.46	2.96	9.15	

Legend: d - diagonal tire or bias crossply tire; r - radial tire; ra - track; ni - low profile tire, height/width 0.6<X<0.8; no - normal profile tire height/width X≥0.8; tr - terra tires height/width 0.6≤X

shown in Table 2. Mean contact pressure was from 42 until 197 kPa. The lesser mean contact pressure was recorded by CASE IH 8800 harvester, due to big ground contact surface of the tracks. The largest contact pressure was of the tipping tow 7CX (SC)-10. This equipment had a high tire inflation pressure (higher than recommended by the manufacturer) and high tire load, two factors with direct influence in contact pressure soil tire. Soil stresses distribution is a function of both factors. Several researches have shown dependence of mean contact stresses and soil stresses distribution from inflation pressure and tire load (Arvidsson and Keller, 2007, Keller, 2005) and some equations have been developed to predict mean contact pressure from inflation pressure. Arvidsson and Keller (2007) researched the maximum stresses caused by agricultural machinery at different soil depth. They found at 10 cm depth, the stress increased with increasing inflation pressure and with increasing wheel load.

Maximum vertical stresses were found in contact area tire-soil. These are propagated in depth. For soft clay soil TASC V3.0 stablish a stability point where the soil response is elastic when pressures transmitted are lesser than 80 kPa. Soil compaction occurs when pressure transmitted to soil exceeds the corresponding soil reaction force represented here by stability point, that can be the precompressive pressure. No severe soil compaction occurs if the vertical pressures caused by machinery are lower than precompressive pressure or stability point (Guimarães Júnnyor *et al*., 2019). Figure 1 and 2 shows soil pressures transmission

TABLE 2. Results of mean contact pressure, severe soil compaction and maximum vertical stresses

Machinery	Axle	Tire Size	Results from TASC V3.0		
			Mean Contact Pressure (kPa)	Severe soil compaction Risk up to depth (m)	Maximum Vertical Stress (kPa)
Tractor XTZ 150K-09	Front	21.3-24	103	0.24	179
Tractor XTZ 150K-09	Rear	21.3-24	98	0.23	170
YTO 1604	Front	460/85R34	75	0.19	130
YTO 1604	Rear	18.4-38	166	0.31	288
Tipping Tow 7CX (SC)-10	Front	600/50-22.5	197	0.37	342
Tipping Tow 7CX (SC)-10	Rear	600/50-22.5	196	0.32	340
CASE IH 8800		Track	42	0	72

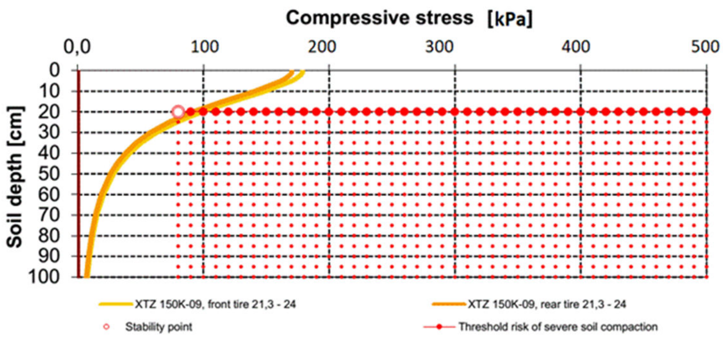

FIGURE 1. Soil pressure propagation of the tractor XTZ 150K-0.9.

and pressure bulbs for the tractor XTZ 150K-0.9. Pressures higher than 80 kPa are found until a depth of 0.24 and 0.23 m for front and rear tire respectively, therefore severe soil compaction risk up to these depths. From these depths no soil compaction occurs.

The Figure 2 shows pressure bulbs for the rear tire of tractor XTZ 150K-09. Soil has similar response for rear and front tire of this tractor due to tire size is the same from both axle and tire load is quite similar. Maximum pressures were obtained in soil surface, raising 179 y 170 kPa. Soil compaction occurs until 0.24 m for front tire y until 0.23 m from rear tire, almost in the zone of maximum tillage depth.

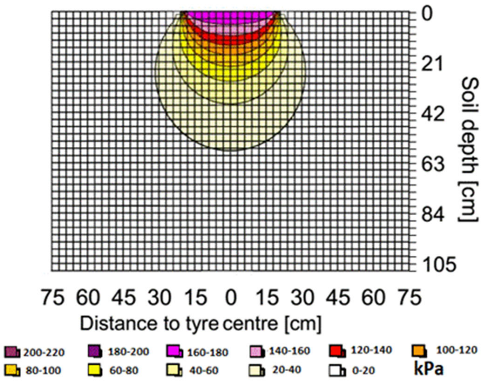

FIGURE 2. Pressure bulbs for the rear tire of tractor XTZ 150K-09.

The tractor YTO 1604 shows a difference in soil response for front and rear tire. Although tire size are some similar, the difference is made by tire load with almost 1 Mg more in rear tire respect to front tire. This make that mean contact pressure of rear tire (288 kPa) is almost double respect to front tire (130 kPa) (Table 2). Figure 3 shows compressive pressures in soil under tractor YTO 1604 and CASE IH 8800. Both harvester and tractor front tire do not cause compaction of the agricultural soil, under the maximum tillage layer. Even on the soil surface the harvester does not cause compaction. The front tire causes compaction up to a depth of 0.19 m (Table 2), that is, in the tillage layer. However, rear tire of YTO 1604 cause soil compaction until a depth of 0.31 m.

The Figure 4 shows pressure bulbs in soil under front and rear tire of the YTO 1604. For front tire bulbs pressure higher than stability point only occurs in surficial layer. For rear tire is observed a high pressure higher than 100 kPa in all tillage layer, raising the risk of severe soil compaction until 0.31 m of depth.

The Figure 5 shows pressure bulbs caused by tipping tow, here is observe the high pressure in the soil - tire contact. Mean contact pressures are similar, 197 and 196 kPa and maximum vertical stresses are similar too, 342 y 340 kPa respectively; however risk of severe soil compaction were 0.37 and 0.32 m, 5 centimeters more in front tire respect to rear tire. Although the pressure in the soil-tire contact is similar, the depth to which severe compaction occurs is much greater in the case of the front tire because it applies a greater load on the soil by 850 kg. The representation of the pressure bulbs show that stresses not only propagate in depth below the tire center, but they also propagate on the sides with respect to the axis wheel, that is, perpendicular to the direction of progression. This occurs precisely because the pressure exerted on the soil displaces the particles toward the deeper layers but at the same time does so toward the sides, producing lateral compaction that, although not as severe as that produced in the lower layers, does affect the soil physical properties.

When analyzing these results, we found that both the harvester, the XTZ 150K-09 tractor and the front tire of the tractor YTO 1604 compact only the soil tillage layer. In seasonal crops, this compaction does not affect the crop because the soil is tilled at the end of the harvest. However, in the case of sugarcane, this does not happen, and this layer of soil will have to be decompacted with deep cultivation work or decompaction between rows, carrying out work that demands a large amount of energy from the tractor. From these results can be propose to decompaction until a depth of 0.37 m. Until this depth occurs severe soil compaction.

The high potential for the tipping tow and rear tire of the YTO 1604 to cause soil compaction is related with the high load carried by the wheels, which causes the pressures applied to soil is extend deeper into

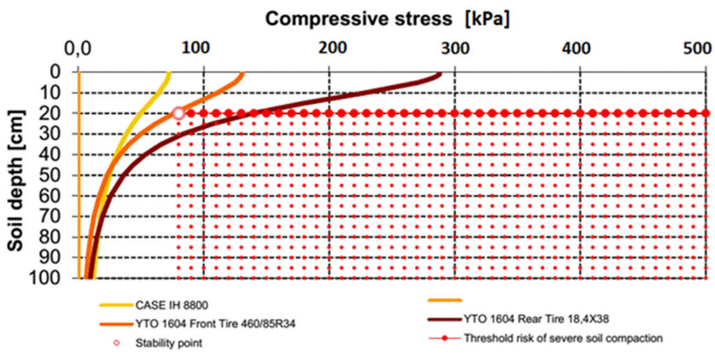

FIGURE 3. Soil pressure propagation of the tractor YTO 1604 and CASE IH 8800.

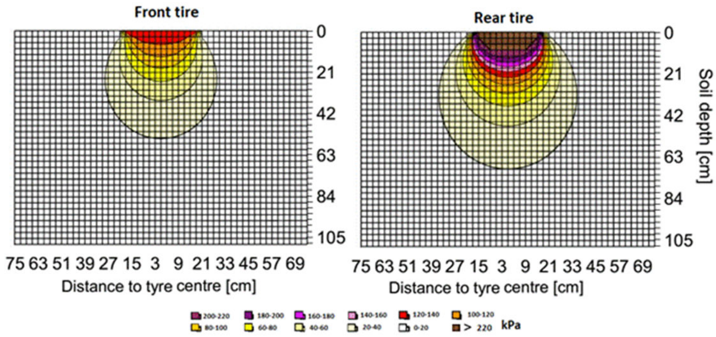

FIGURE 4. Pressure bulbs for the front and rear tire of tractor YTO 1604.

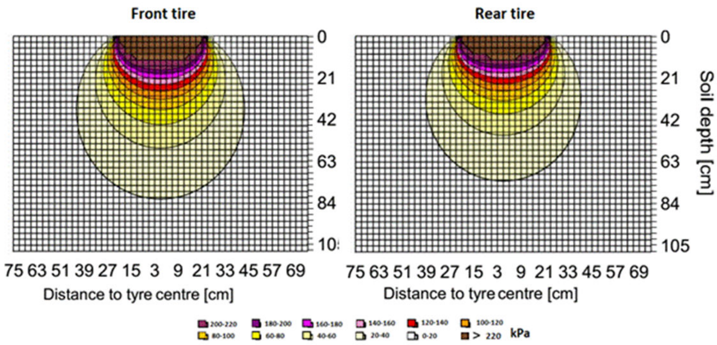

FIGURE 5. Pressure bulbs for the front and rear tire of tipping tow.

the vertical profile. Some researchers have described as soil pressure propagation to layers more depth is mainly a resulted of axle load (González et al., 2016, Botta et al., 2002).

The results obtained here are also consistent with those of Botta *et al.* (2002), who describe that the pressure in the wheel-soil contact zone can influence surface compaction, while at a depth equal to or greater than 40 cm, the weight on the axle, regardless of the pressure on the ground, is the main cause of the compaction process and Hakansson and Reeder (1994), who found a strong and direct dependence of surface compaction on the pressure in the wheel-soil contact area.

Of the equipment evaluated, the tipping tow is the one that causes soil compaction at the greatest depth and the one that represents the greatest risk of severe soil compaction. A solution to soil compaction caused by this medium could be to use it up to a medium load, which would reduce compaction. However, the best variant would be to use it only on firm or dry soils and to replace it with a trailer with a lower load capacity and a lower total weight on the axles during harvesting in high moisture content.

CONCLUSIONS

The use of modelling TASC V3.0 permitted to predict soil compaction caused by harvesters and transport equipment during sugarcane harvest on soft clay soil. More severe soil compaction was obtained during use of tipping tow 7CX (SC)-10 due to high mean contact pressure and high tire load, which caused severe soil compaction reaching 0.37 m of depth. Rear tire of tractor YTO 1604 caused severe soil compaction too reaching 0.31 m of depth. In general sense all equipment caused severe soil compaction in tillage layer, therefore must be make decompactions works until a depth of 0.37 m, with the objective to loose soil in depth for a good developed of sugarcane ratoons.

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